# W4118: interrupt and system call

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References: Modern Operating Systems (3rd edition), Operating Systems Concepts (8th edition), previous W4118, and OS at MIT, Stanford, and UWisc

# Outline

- Motivation for protection
- Interrupt
- System call

# Need for protection

- Kernel privileged, cannot trust user processes
  - User processes may be malicious or buggy

- Must protect
  - User processes from one another
  - Kernel from user processes

# Hardware mechanisms for protection

- Dual model of operation
  - Privileged (+ non-privileged) operations in kernel mode
  - Non-privileged operations in user mode
- Memory protection
  - Segmentation and paging
    - E.g., kernel sets page table when creating process
- Timer interrupt
  - Kernel periodically gets back control

# What operations are privileged?

- Read raw keyboard input
- Call printf()
- Call write()
- Write global descriptor table
- Divide by 0
- Set timer interrupt handler
- Set segment registers
- Load cr3

# x86 protection modes

- Four modes (0-3), but often only 0 & 3 used
  - Kernel mode: 0
  - User mode: 3
  - “Ring 0”, “Ring 3”
- Segment has Descriptor Privilege Level (DPL)
  - DPL of kernel code and data segments: 0
  - DPL of user code and data segments: 3
- Current Privilege Level (CPL) = current code segment’s DPL
  - Can only access data segments when CPL <= DPL

# Outline

- Motivation for protection
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# OS: "event driven"

- Events causing mode switches
  - System calls: issued by user processes to request system services
  - Exceptions: illegal instructions (e.g., division by 0)
  - Interrupts: raised by devices to get OS attention

- Often handled using same hardware mechanism: interrupt
  - Also called trap

# Interrupt view of CPU

```
while (fetch next instruction) {
    run instruction;
    if (there is an interrupt) {


        process interrupt


    }
}
```

# x86 interrupt view

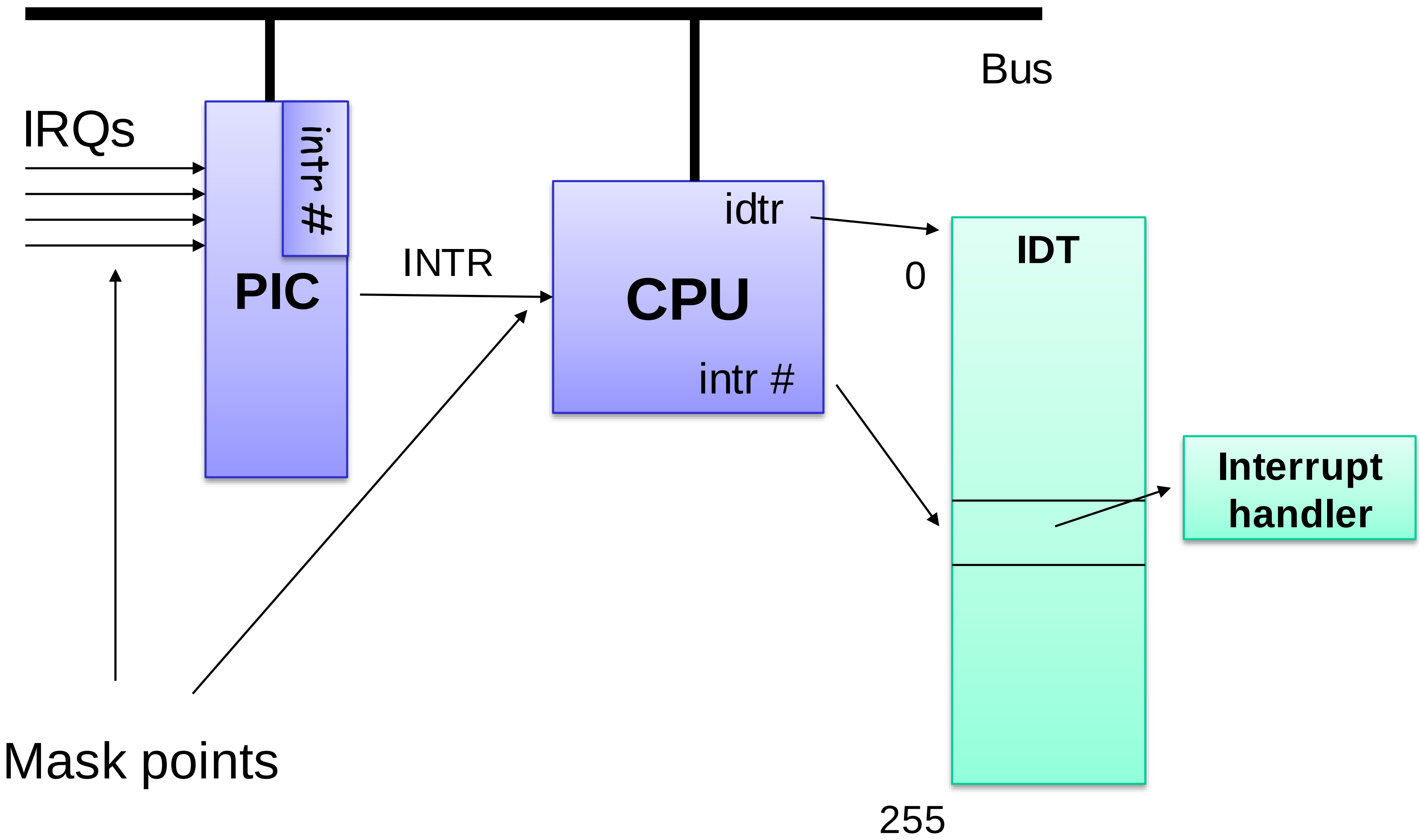
```
while (fetch next instruction) {
    run instruction;
    if (there is an interrupt) {
        switch to kernel stack if necessary
        save CPU context and error code if any
        find OS-provided interrupt handler
        jump to handler
        restore CPU context when handler returns
    }
}
```

- Q1: how does hardware find OS-provided interrupt handler?
- Q2: why switch stack?
- Q3: what CPU context to save and restore?
- Q4: what does handler do?

# Q1: how to find interrupt handler?

- Hardware maps interrupt type to interrupt number
- OS sets up Interrupt Descriptor Table (IDT) at boot
  - Also called interrupt vector
  - IDT is in memory
  - Each entry is an interrupt handler
  - OS lets hardware know IDT base
  - Defines all kernel entry points
- Hardware finds handler using interrupt number as index into IDT
  - handler = IDT[intr_number]

# x86 interrupt hardware (legacy)



# x86 interrupt numbers

- Total 256 number [0, 255]

- Intel reserved first 32, OS can use 224
  - 0: divide by 0
  - 1: debug (for single stepping)
  - 2: non-maskable interrupt
  - 3: breakpoint
  - 14: page fault
  - 64: system call in xv6
  - xv6 traps.h

# x86 interrupt descriptor table

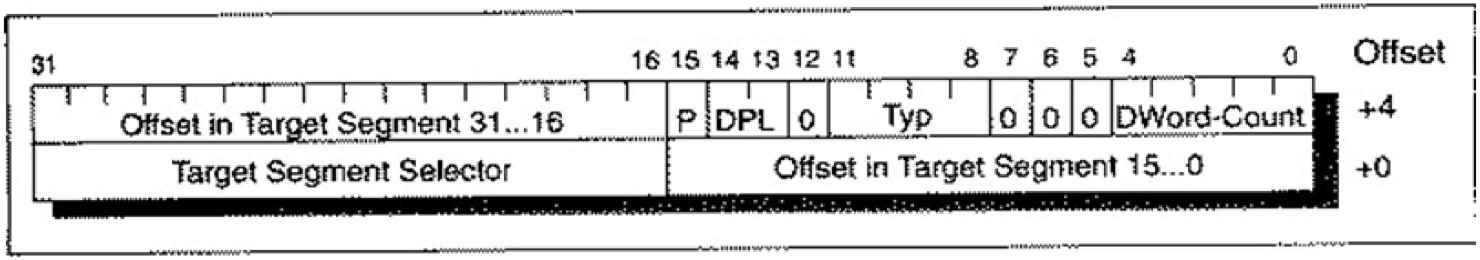


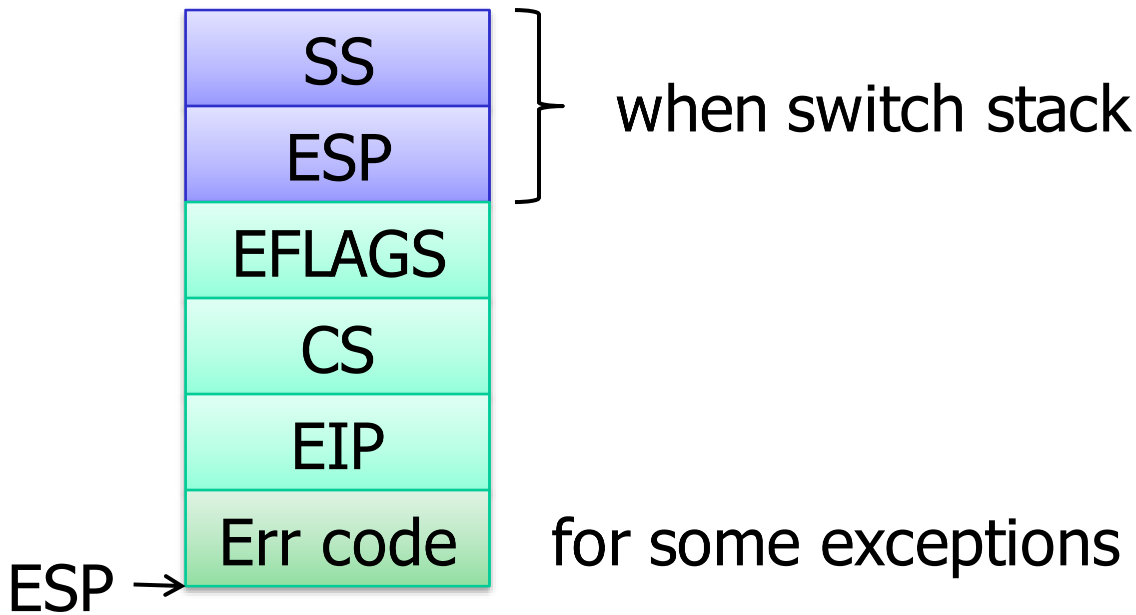

*Figure 3.12: Format of an i386 gate descriptor.*

- Interrupt gate descriptor
  - Code segment selector and offset of handler
  - Descriptor Privilege Level (DPL)
    - To invoke "int x" in software, must have CPL <= DPL
  - Trap or exception flag. If exception, hardware clears the IF flag in EFLAGS to disable further maskable interrupts
- lidt instruction loads CPU with IDT base
- xv6
  - Handler entry points: vector.S
  - Interrupt gate format: SETGATE in mmu.h
  - IDT initialization: tvinit() & lidt() in trap.c

# Q2: why switch stack?

- Cannot trust stack of user process!
- x86 hardware switches stack when interrupt handling requires user-kernel mode switch
  - That is, when CPL <= DPL of handler's code segment
- Where to find kernel stack?
  - task gate descriptor has SS and ESP for interrupt
  - ltr loads CPU with task gate descriptor
- xv6 uses current process's kernel stack
  - switchuvm() in vm.c

# Q3: what CPU context to save and restore?




- x86 saves SS, ESP, EFLAGS, CS, EIP, Err code
- Restored by iret
- OS can save more context

# Q4: what does interrupt handler do?

- Typical steps
  - Assembly to save additional CPU context
  - Invoke C handler to process interrupt
    - E.g., communicate with I/O devices
  - Invoke kernel scheduler
  - Assembly to restore CPU context and return

- xv6
  - Interrupt handler entries: vector.S
  - Saves & restore additional CPU context: trapasm.S
  - C handler: trap.c, *struct trapframe* in x86.h

# Interrupt v.s. Polling

- Instead for device to interrupt CPU, CPU can poll the status of device
  - Intr: "I want to see a movie."
  - Poll: for(each week){"Do you want to see a movie?"}

- Good or bad?
  - For mostly-idle device?
  - For busy device?

# Outline

- Motivation for protection
- Interrupt
- System call

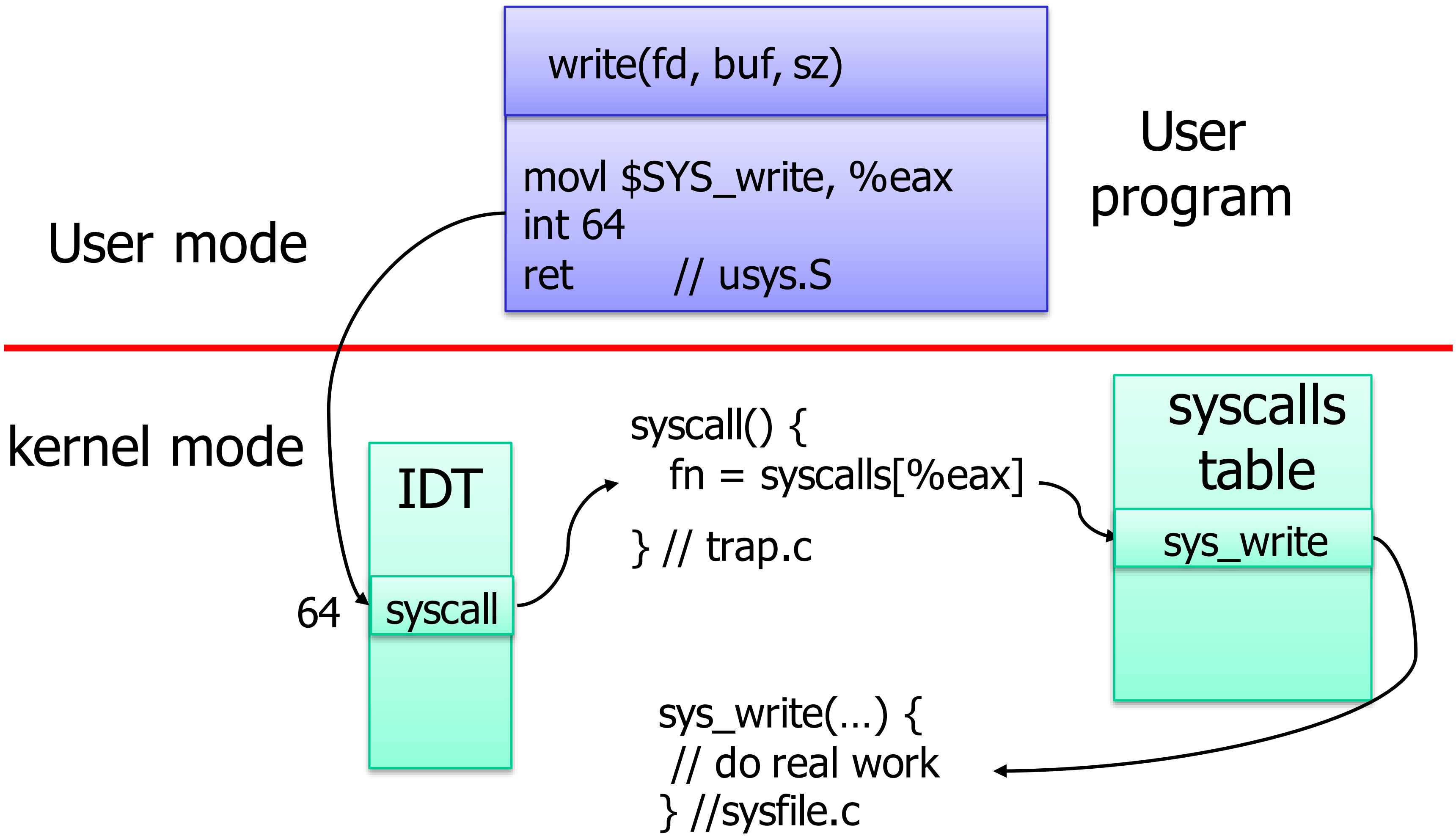
# System call

- User processes cannot perform privileged operations themselves
- Must request OS to do so on their behalf by issuing system calls
- OS must validate system call parameters

# System call dispatch

1. Kernel assigns system call type a system call number
2. Kernel initializes system call table, mapping system call number to functions implementing the system call
   - Also called system call vector
3. User process sets up system call number and arguments
4. User process runs int X
5. Hardware switches to kernel mode and invokes kernel's interrupt handler for X (interrupt dispatch)
6. Kernel looks up system call table using system call number
7. Kernel invokes the corresponding function
8. Kernel returns by running iret (interrupt return)

# xv6 system call dispatch



# System call parameter passing

- Typical methods
  - Pass via registers (e.g., Linux)
  - Pass via user-mode stack (e.g., xv6)
  - Pass via designated memory region

- xv6 system call parameter passing
  - Arguments pushed onto user stack based on gcc calling convention
  - Kernel function uses special routines to fetch these arguments
    - syscall.c
    - Why?

# xv6 system call naming convention

- Usually a library function foo() will do some work and then call a system call sys_foo()
  - sys_foo() implemented in sys*.c
  - Often wrappers to foo() in kernel

- System call number for foo() is SYS_foo
  - syscalls.h

- All system calls begin with sys_

# Tracing system calls

- Use the “strace” command (man strace for info)
- Linux has a powerful mechanism for tracing system call execution for a compiled application
- Output is printed for each system call as it is executed, including parameters and return codes
- ptrace() system call is used to implement strace
  - Also used by debuggers (breakpoint, singlestep, etc)
- Use the “ltrace” command to trace dynamically loaded library calls